Moderate-Resolution Imaging Spectroradiometer ocean color polarization correction

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The polarization correction for the Moderate-Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua satellites is described. The focus is on the prelaunch polarization characterization and on the derivation of polarization correction coefficients for the processing of ocean color data. The effect of the polarization correction is demonstrated. The radiances at the top of the atmosphere need to be corrected by as much as 3.2% in the 412 nm band. The effect on the water-leaving radiances can exceed 50%. The polarization correction produces good agreement of the MODIS Aqua water-leaving radiance time series with data from another, independent satellite-based ocean color sensor, the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS).

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1. Introduction

NASA's Earth Observing System (EOS) satellites Terra[1] and Aqua[2] each carry a Moderate-Resolution Imaging Spectroradiometer[3] (MODIS) that produces global coverage every 2 days with a nadir spatial resolution of 1 km for the nine ocean color bands. The Ocean Biology Processing Group[4] (OBPG) at NASA's Goddard Space Flight Center has been responsible for processing the MODIS ocean color data since early 2004. The authors of this paper are members of that group. Our goals in this paper are to describe the implementation of the results of the prelaunch polarization characterization and to demonstrate the importance of the polarization correction to the MODIS ocean color products.

The wavelengths of the MODIS ocean color bands are given in Table 1. MODIS scans the Earth from its polar orbit, with a scan perpendicular to the flight direction. The MODIS polarization sensitivity was characterized prelaunch for several viewing angles for the ocean color bands. Interactions between polarization and the response versus viewing angle are discussed by Knight *et al.*[5]

Normalized water-leaving radiances (L_{WN}; see Wang *et al.*[6] for a definition) are the basic ocean color products. The atmospheric correction is the main challenge when one is converting measured top-of-atmosphere (TOA) radiances (I_m) to L_{WN}. The polarization components of the TOA radiances are modeled separately for Rayleigh scattering from the atmosphere and glint from the ocean surface; then they are summed to provide total polarization components (Q_t and U_t; see below). Rayleigh and glint radiances are modeled by the successive-order-of-scattering method applied to the vector radiative transfer equation to account for polarization, assuming a Rayleigh-scattering atmosphere overlying a Fresnel-reflecting ocean surface.[7] The ocean surface's roughness is derived from the wind speed.[8] The measured TOA radiances are corrected by use of the instrument's prelaunch polarization characterization and the modeled polarization components of the TOA radiances (see Fig. 1), which assumes that polarization components caused by aerosol scattering and water-leaving radiances are negligible. We expect that future algorithms will allow us to improve on this assumption.

The degree of polarization of the modeled TOA radiance varies strongly with scattering angle, typically from 0% to 70%. The response of the MODIS Aqua varies by as much as $\pm 5.4\%$ for completely polarized light (depending on the direction of the electric field vector relative to the MODIS); see Table 2. The average contribution of Rayleigh scattering to TOA radiances with $\geq 70\%$ degree of polarization is $\sim 80\%$ at 412 nm. Thus, for the MODIS, the measured TOA radiance must be corrected by as much as $\pm 3.0\%$ ($= \pm 5.4\% \times 0.7 \times 0.8$). The desired total accuracy for the TOA radiances of the ocean color bands is 0.5% or better; thus the need for an accurate polarization correction is obvious. The vicarious calibration used for ocean color sensors[10] can correct constant calibration offsets only, not variable effects such as polarization. Comparisons with data from other satellite sensors are a useful validation tool, but, especially for the atmospheric correction bands (15 and 16), these comparisons are problematic. Thus an accurate prelaunch polarization characterization is essential in meeting the ocean color data quality requirements.

The prediction of the TOA polarization components has been described by Gordon *et al.*,[9] as has the basic correction algorithm. We follow the conventions and notation used there. In this paper we present a slightly improved algorithm. The focus of this paper is on the analysis of the prelaunch characterization and its effect on the MODIS Aqua ocean color data products. Because of an incorrect interpretation of the prelaunch characterization, an erroneous polar-

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Table 1. Center Wavelengths and Bandwidths for the MODIS Aqua Ocean Color Bands and the SeaWiFS[a]

MODIS Band Number	MODIS Center Wavelength (nm)	MODIS Bandwidth (nm)	SeaWiFS Center Wavelength (nm)	SeaWiFS Bandwidth (nm)
8	412	15	412	20
9	443	10	443	20
10	488	10	490	20
11	531	10	510	20
12	551	10	555	20
13L[b]	667	10	670	20
14L	678	10		
15	748	10	765	40
16	870	15	865	40

[a]Sea-Viewing Wide Field-of-View Sensor.
[b]L denotes low-gain output.

Table 2. Measured MODIS Aqua Polarization Amplitude p_a [Eq. (13)], Estimated Standard Uncertainty (k = 1) of the Modeled Polarization Sensitivity σ_P [Eq. (11)], and MODIS Aqua Polarization Phase Angle δ [Eq. (1)][a]

Band	Mean(p_a)	Max(p_a)	σ_P	Mean(δ) (°)
8	0.045	0.054	0.002	−10
9	0.023	0.031	0.005	−15
10	0.011	0.011	0.01	−8
11	0.009	0.013	0.008	−23
12	0.013	0.020	0.006	83
13L	0.008	0.008	0.01	−34
14L	0.009	0.012	0.01	−9
15	0.005	0.007	0.01	18
16	0.018	0.025	0.005	84

[a]The statistics for p_a and δ are calculated for the prelaunch measurement viewing angles.

ization correction was applied for the ocean color products distributed before February 2004. This error severely compromised a significant portion of the MODIS ocean color products. We show the improvement gained by application of the rectified polarization correction by comparing the water-leaving radiances from the MODIS Aqua with those from the SeaWiFS,[11] which has a nominal polarization sensitivity of ~0.25%, a factor of 20 less than the maximum polarization sensitivity of the MODIS.

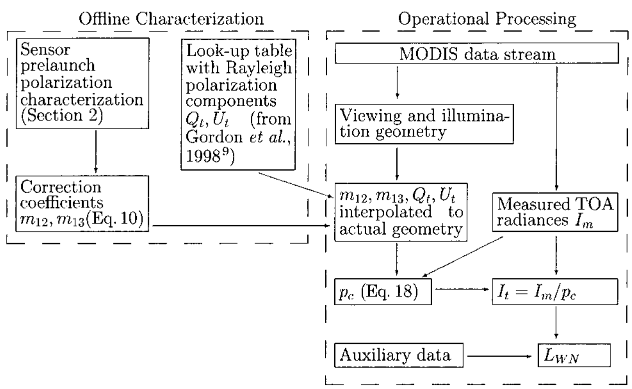

Fig. 1. Flow chart of the MODIS Aqua ocean color polarization correction.

5. Conclusions and Outlook

The polarization characterization of a large aperture instrument such as the MODIS is a technological challenge. In this paper we have highlighted several problems of the prelaunch characterization measurements; see Figs. 4–6 (detector variations, lack of two-cycle pattern, four-cycle effect). However, there is now no clear evidence that the derived polarization correction yields significantly incorrect results for the MODIS Aqua ocean color products. These products are highly sensitive to polarization because ~90% of the signal in the ocean color bands is due to the atmosphere, which often includes a highly polarized contribution from Rayleigh scattering. In effect, the current polarization correction is essential for the good agreement between the MODIS Aqua and SeaWiFS time series, especially for the short wavelengths at high latitudes; see Fig. 11. The polarization correction significantly reduces the occurrence of negative L_{WN} at 412 nm.

For most ocean color bands, the typical mean TOA radiance polarization correction is ~0.2%, and the maximum polarization correction is ~1%; see Table 3. Bands 8 and 9 have significantly higher corrections. Globally, the range of variation of the polarization correction varies from 0.7% (bands 13 and 15) to 5.4% (band 8) for the MODIS Aqua ocean color bands. The strong spatial and temporal variations of the band 8 polarization correction are shown in Figs. 9(e) and 9(f).

The current implementation of the polarization correction is entirely based on the prelaunch polarization measurements. Future implementations may be based on an improved understanding of the MODIS polarization sensitivity derived from ray tracing models or from pixel-based comparisons to SeaWiFS, which may provide detector-specific polarization coefficients, a time-varying polarization sensitivity that reflects the on-orbit degradation[28] of the MODIS optics, or a different algorithm to process the prelaunch measurements.

The polarization characteristics of aerosols are ignored in the current processing. Howard Gordon (hgordon@miami.edu) of the University of Miami is working on aerosol scattering models to include these effects. The models will provide the Q_t and U_t polarization components produced by aerosol scattering for TOA radiances. These components will be added to the polarization components produced by Rayleigh scattering and glint. Other refinements in the processing, such as the improvement of ocean bidirectional reflectance distribution function BRDF corrections, are being assessed as well.

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